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# Beyond Standard Model Higgs boson physics with the ATLAS experiment at the LHC

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## ABSTRACT

The search for evidence of beyond Standard Model Higgs bosons is an integral part of the Higgs boson studies at the LHC. This article reviews recent beyond Standard Model Higgs boson searches using Run I LHC proton-proton collision data recorded by the ATLAS detector. In particular, searches for Higgs boson cascades, double Higgs boson production, scalar particles decaying to  $\gamma\gamma$  pairs, flavor changing neutral currents involving Higgs bosons, and Higgs bosons decaying to invisible particles are discussed. No significant deviations from the background expectations are found and corresponding constraints on physics beyond the Standard Model are obtained.

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# 1 Introduction

The recent observation of a new particle with mass 125–126 GeV at the LHC [1,2] opens a new era for particle physics. The detailed study of the production and decay modes of the new particle provides invaluable input to answer the question of whether this is indeed the long-sought Standard Model (SM) Higgs boson [3–8]. The first measurements indicate that the new particle is indeed compatible with the SM Higgs boson, see e.g., [9]. Nevertheless, many more measurements and data will be needed to extract reliable conclusions. This task is further complicated by the fact that many beyond SM physics scenarios include a SM-like Higgs boson, which is part of an extended scalar sector. In that case, searches for beyond SM Higgs bosons are very interesting, since they provide direct information on a possibly extended scalar sector, and hence they are complementary to the precise measurements of the properties of the new particle.

This article reviews some of the recent searches for beyond SM Higgs bosons or exotic properties of the recently discovered Higgs boson using proton-proton collision data at 7 and 8 TeV center-of-mass energies as recorded by the ATLAS detector [10].

## 2 Higgs Bosons in beyond SM physics scenarios

The scalar sector of the SM consists of a complex Higgs doublet, which after the electroweak symmetry breaking leaves a single scalar boson in the theory. Possible extensions of the scalar sector are restricted due to the fact that, in general, they include unacceptably large corrections to the well-measured quantity  $\rho \equiv m_W^2/(m_Z^2 \cos^2 \theta)$ , where  $\theta$  is the weak mixing angle [11]. The addition of doublets or singlets is such that leading order corrections to  $\rho$  vanish and, hence they can be compatible with precision electroweak tests [12].

The introduction of one additional Higgs doublet defines a class of models, which are collectively known as 2 Higgs doublet models (2HDM) [13]. These models introduce five Higgs bosons, three of which are neutral and two of which are charged. The Minimal Supersymmetric Standard Model (MSSM) [14–17], which is a very popular realization of supersymmetry, is a particular case of a 2HDM. The MSSM, as well as other 2HDMs, are compatible with existing measurements, including the recently discovered Higgs boson [18,19].

Apart from the introduction of new particles, extensions of the SM scalar sector may affect the properties of the SM-like Higgs boson discovered at the LHC. Enhancement of rare decays, completely new decays and production mechanisms, and different couplings with respect to the SM expectations are possible and may indicate connections to other puzzles, such as dark matter (e.g., see Ref. [20] and references therein).

In the following, only a few recent ATLAS searches are described. As a convention, the symbol  $h$  will refer to the newly discovered Higgs boson with mass  $\sim 125$  GeV.

## 3 Some recent searches for beyond SM Higgs bosons with ATLAS

The existence of an extended scalar sector with more than one Higgs bosons opens the possibility of cascade decays in which heavier Higgs bosons decay into lighter ones. In this context, a Higgs boson cascade has been looked for in Ref. [21] using 20.3 fb<sup>-1</sup> of 8 TeV proton-proton collision data. A heavy Higgs boson is produced via gluon-gluon fusion and initiates a cascade decay that includes a charged scalar,  $H^\pm$ , a light neutral Higgs boson,  $h$ , and  $W$  bosons:  $H \rightarrow W^- H^+ \rightarrow W^- W^+ h$ , see Fig. 1(a). The light neutral Higgs boson decays to  $b\bar{b}$  and it is assumed to have mass 125 GeV. The first of the  $W$  bosons decays leptonically and provides a way to trigger the events whereas the second one decays hadronically maximizing the branching ratio. The final state shares the same topology with  $t\bar{t}$  events with similar  $W$  boson decays, which is the main background process for the search. A multivariate discriminant is employed to exploit the kinematic differences between signal and  $t\bar{t}$  events. Upper limits on the production cross section of heavy neutral Higgs boson,  $H$ , times the branching ratio  $\text{BR}(H \rightarrow W^\mp H^\pm \rightarrow W^\mp W^\pm h \rightarrow W^\mp W^\pm b\bar{b})$  are derived as a function of its mass and the charged scalar mass, as shown in Fig. 1(b).

The pair production of Higgs bosons is very interesting and can be enhanced due to the resonant decay of a heavy CP-even Higgs boson ( $H \rightarrow hh$ ), e.g., in a 2HDM, or even in a non-resonant way, e.g., in composite Higgs boson models [22]. The analysis described in Ref. [23] uses 20.3 fb<sup>-1</sup> of 8 TeV proton-proton collision

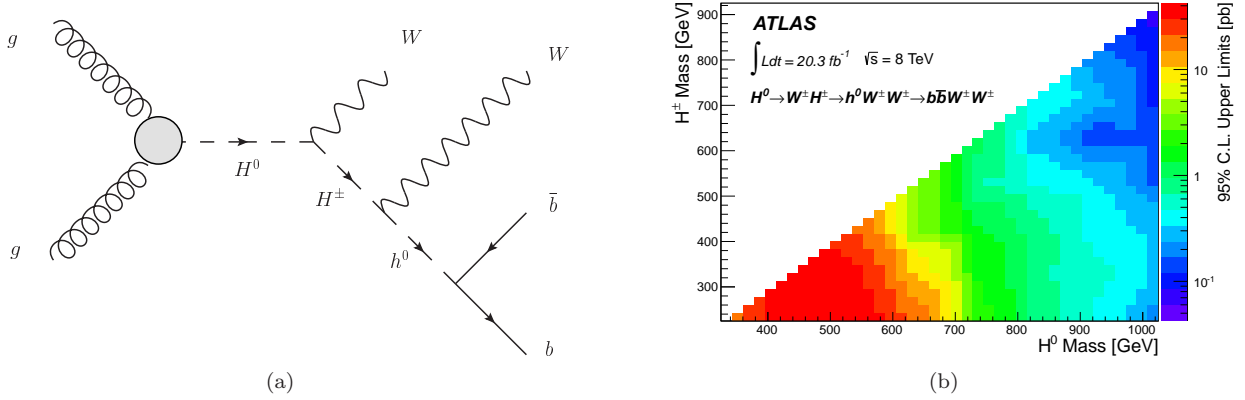


Figure 1: The topology of a Higgs cascade search, described in Ref. [21], is shown in (a). The observed upper limit for this process is shown in (b).

data to look for  $hh$  production in the  $h \rightarrow b\bar{b}$  and  $h \rightarrow \gamma\gamma$  channel. Both resonant and non-resonant anomalous production of  $hh$  pairs is searched for. Upper limits on the production of a narrow-width heavy scalar boson decaying to  $hh$  as a function of its mass are shown in Fig. 2. The cross section for non-resonant  $hh$  production is constrained to be less than 2.2 pb at 95% confidence level. As a reminder, the SM  $hh$  production cross section is  $\sim 10$  fb, i.e., about two orders of magnitude smaller than the sensitivity of this search.

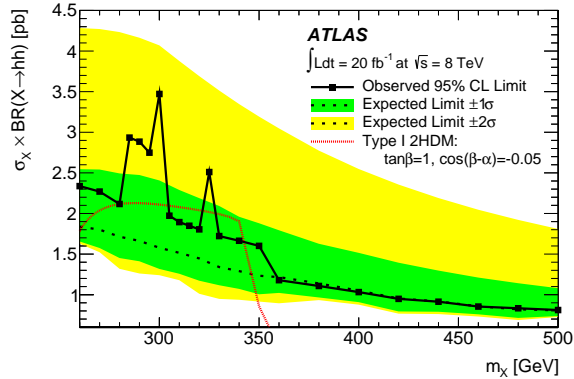


Figure 2: Upper limits from the search for a scalar particle decaying to  $hh$  in the  $b\bar{b}\gamma\gamma$  channel from Ref [23].

A search for a scalar particle that decays to a  $\gamma\gamma$  pair and is in the mass range 65–600 GeV is described in Ref. [24] and uses  $20.3 \text{ fb}^{-1}$  of 8 TeV proton-proton collision data. This analysis considers the SM-like Higgs boson at  $\sim 125$  GeV as a background to the search. Analytical functions are employed to describe the shape of the  $\gamma\gamma$  invariant mass similar to those used in the SM Higgs boson search in the  $\gamma\gamma$  channel [1]. The  $\gamma\gamma$  mass range of this search is constrained by trigger and background estimation requirements from the low mass side and by the data statistics in the high mass side. Upper limits on the fiducial cross section times the branching ratio  $H \rightarrow \gamma\gamma$  are quoted, see Fig. 3.

Flavor changing neutral currents (FCNC) are in general enhanced in extended Higgs sectors. In several occasions, models can be built that evade the tight constraints on FCNC by flavor physics, like the type-III 2HDM [19]. In those cases, the  $thc$  coupling is predicted to be sizeable and close to the LHC sensitivity [25]. A search for top quark decaying to  $hq$ , where  $q$  denotes some light quark, is reported in Ref. [26] and uses  $4.7 \text{ fb}^{-1}$  of 7 TeV and  $20.3 \text{ fb}^{-1}$  of 8 TeV proton-proton collision data. This analysis looks for  $t\bar{t}$  production in which one top decays to  $hq$  and the other semileptonically or in a fully hydronic way. An example of the  $\gamma\gamma$  invariant mass after all selection requirements for the case where one of the tops decays in a fully

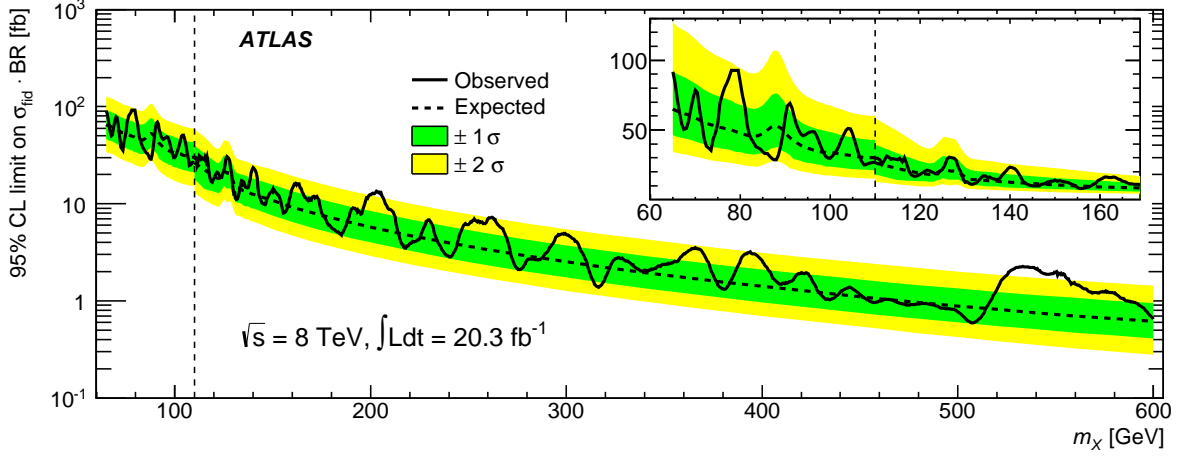


Figure 3: Upper limits at 95% confidence level of a search for a scalar particle decaying to a  $\gamma\gamma$  pair from Ref. [24].

hydropic way is shown in Fig. 4(a). The observed (expected) upper limit at 95% confidence level for the flavor changing branching ratio is  $\text{BR}(t \rightarrow hq) < 0.79(0.51)\%$ , see Fig. 4(b).

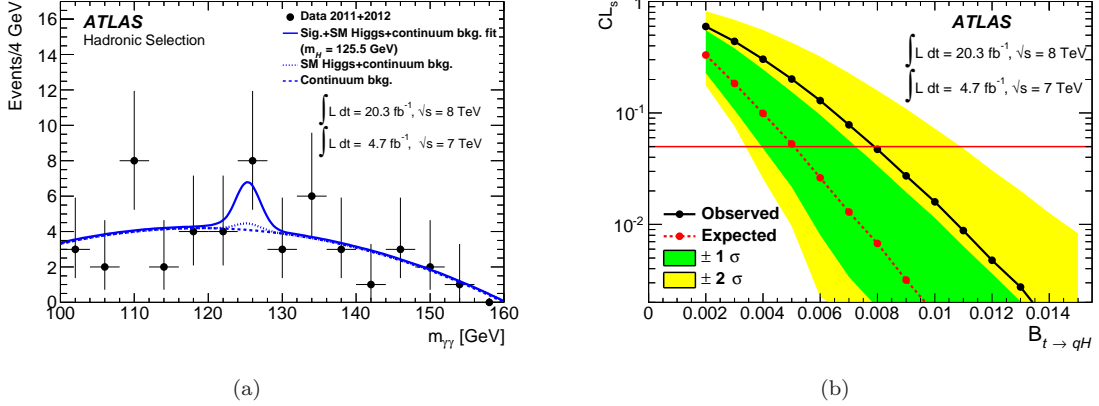


Figure 4: The distribution of the  $\gamma\gamma$  mass for  $t\bar{t} \rightarrow hqWb$  candidates in which the  $W$  boson decays hadronically is shown in (a). Observed and expected CLs for the  $t \rightarrow hq$  search is shown in (b). Both figures are from Ref. [26].

A search for invisible decays of the Higgs boson discovered at the LHC can provide access to dark matter through the Higgs portal [27]. A search reported in Ref. [28] uses  $4.5 \text{ fb}^{-1}$  of 7 TeV and  $20.3 \text{ fb}^{-1}$  of 8 TeV proton-proton collision data to look for the associated production of a Higgs boson with a  $Z$  boson as shown pictorially in Fig. 5(a). The  $Z$  boson decays to an electron or a muon pair and the Higgs boson is assumed to decay to invisible particles. The final event sample is dominated by  $Z$ +jet events and the missing transverse momentum distribution is examined for discrepancies with respect to the SM prediction, see Fig. 5(b). Upper limits for the production of a Higgs boson in association with a  $Z$  boson, assuming that the Higgs boson decays always to invisible particles, are shown in Fig. 5(c). This result is combined with indirect constraints on invisible Higgs boson decays from Higgs boson coupling measurements [29]. The observed (expected) combined constraint for the 125 GeV Higgs boson on the invisible branching ratio is  $\text{BR}(h \rightarrow \text{invisible}) < 37(39)\%$  at 95% confidence level.

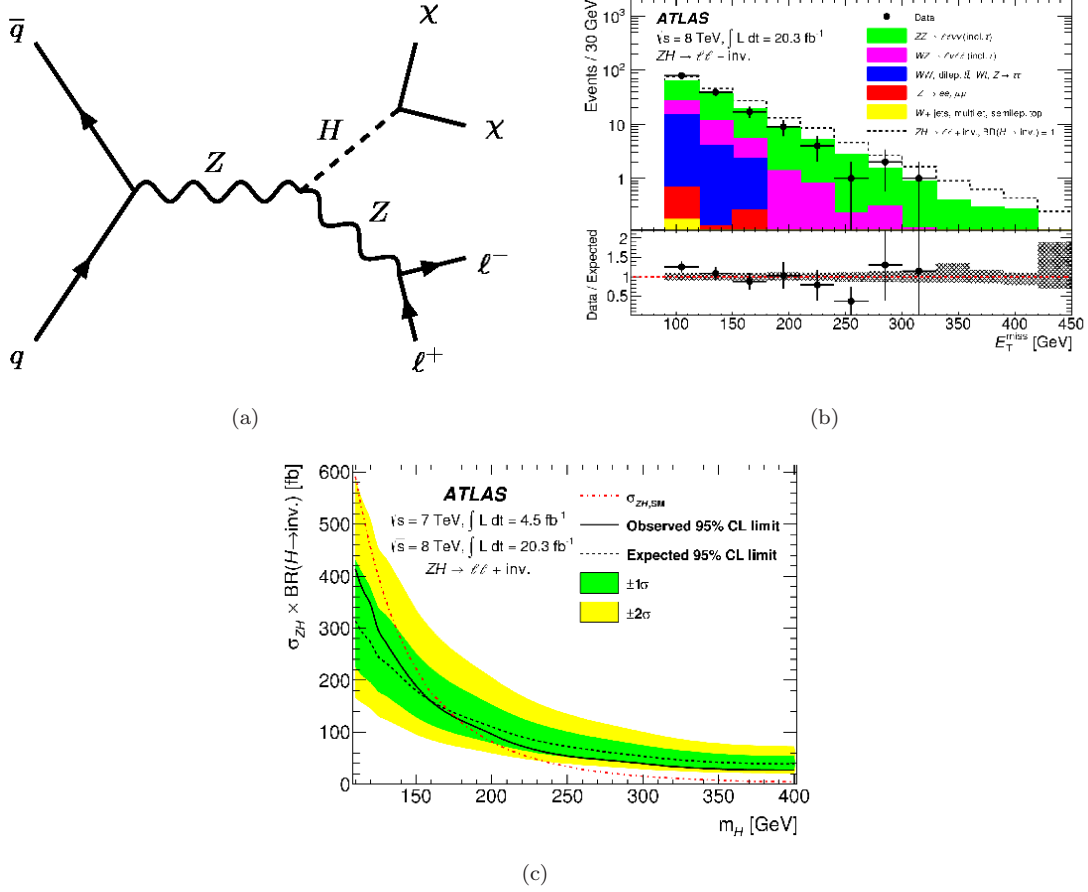


Figure 5: The topology of the search for invisible Higgs boson decays described in Ref. [28] is shown in (a). The missing transverse momentum after the full selection and the upper limits on this process are shown in (b) and (c), respectively.

## 4 Conclusions

The search for beyond SM Higgs bosons is highly motivated and has just started having sensitivity to realistic scenarios. The discovery of a Higgs boson with mass around 125 GeV has opened new possibilities for searches, especially those that include the new particle in the final state. More data are needed in order to explore the possibility of an extended scalar sector and, hence the community is looking forward to the new LHC run.

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